The Design Build Experience in the Context of A Self-Consolidating Grout Research Project

A Senior Project

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Abstract:

The purpose of this project was to experience the design-build project delivery method in the context of a research-fueled, procedural testing investigation. Thus, this project consisted of 3 main components each of which will be addressed in this report.

The first aspect to be addressed is the research aspect. The goal of our research was to establish a chemical understanding of how replacement of cement with pozzolans in a grout mixture affects chemical processes and resulting structural characteristics within and of the grout. This research was then applied to formulation of potentially self-consolidating mix designs to be tested in the next aspect of the project.

The next aspect of the project to be addressed is the application of the research to formulation of mix designs followed by the evaluation and analyses of said mix designs. This included ASTM procedurally guided testing of slump flow, j-ring slump flow, visual stability index identification, blocking assessment, compressive testing, and consolidation assessment. The goal of this testing was to establish a self consolidating grout mix design in accordance with ASTM C 476 which defines a self consolidating mix by its performance in terms of slump, visual stability, and compressive strength.

The final aspect of the project to be addressed is the design build experience encountered while carrying out the procedural portion of the project. This will be discussed on the basis of criteria outlined by the Design Build Institute of American, namely 3 key terms assigned to successful design build project delivery, collaboration, integration, and communication. Each of these terms will be discussed in the context of our experience on this project.

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<u>Research:</u>

What is a self-consolidating grout?

Self-consolidating grout mixtures differ from typical grout mixtures in that self-consolidating mixtures yield similar cementitious values, while requiring less physical labor to yield similar consolidation. This self-consolidating grout should be sufficiently workable to flow through congested cells, make adequate bonds between compressive and tensile members, satisfy minimum compressive strength specification, and consolidate with minimal, or negligible, void space. Ultimately, a self-consolidating grout should be capable of consolidation under its own self-weight. This means that no mechanical vibration should be required.

Reducing the labor process for consolidation by mechanical vibration and the need for addition of admixtures increases time and cost efficiency, especially projects in high seismic zones, which require the grouting of every cell. Non-self-consolidating grout mixtures have to be grouted in multiple lifts (heights of 4’ to 6’), and mechanically vibrated along the way. Whereas, self-consolidating grout mixtures push the limits of lift heights to 12’ and require mechanical vibration only at the top where the pressure head is the smallest.

Perhaps most importantly, sustainable self-consolidating grout mixes can be beneficial environmentally. Replacement of cement in grout mixes by pozzolans like fly ash and blast slag promotes sustainability efforts by reducing the demand for cement and thus significantly reducing the amount of carbon dioxide emitted during cement manufacturing. To supplement this, high replacement grouts and concretes have been proven to have a longer life span and thus require less upkeep or replacement efforts.

In our project, potential self-consolidating grout mixes were established on the basis of high replacement of Portland cement by pozzolans—fly ash and blast slag—with no chemical admixtures. The pozzolan replacement allows a reduction in the water to cementitious materials ratio and serves to improve the workability and the flowability of the grout mixture while still retaining potential for strength. The issue with cement replacement by pozzolans is the delay in strength development, being that strength is comfortably defined within the industry by a specified 28 day compressive strength minimum, which is not as easily met with high replacement of cement with pozzolans. Ultimately, what our research is to search for the perfect balance between increased flowability and somewhat retained strength development at the 28-day mark.

Specifically, in accordance with ASTM C476, a self-consolidating grout mixture is one that satisfies the following requirements:

1. A slump flow—as determined by ASTM C1611—between 24 and 30 inches.
2. A visual stability index (VSI)—as determined by appendix XI of ASTM C1611—of no greater than 1.
3. A minimum compressive strength of 2000 psi at 28 days.

These requirements serve as a basic outline for our research. In addition to slump flow, visual stability index, and compressive strength, we also evaluated our mix for consolidation in a 12’ fully grouted, single lift, wall. As previously stated, the goal is to balance acceptable flowability from the slump flow (with regard to segregation, as controlled by the visual stability index) and achieving a 2000 psi minimum 28 day compressive strength. The general rule of thumb is: the higher the replacement of cement with pozzolans, the better the flowability, however, the slower the strength development. In order to explain this phenomenon, a brief description of the hydration process of a traditional grout mix design is given.

What is Hydration?

The hydration of grout is actually the chemical reaction of cement and water, where the process is defined by repetitive cycles of dissolution and precipitation. The process begins with dissolution.

Dissolution

When a grout first begins curing, hydration of the cement begins with a process called dissolution. In this phase of hydration, the highly soluble cement rapidly begins to dissolve, releasing ions into the water within the mix. Eventually, the concentration increases until the solution reaches supersaturation, at which point, the solution is at a very high-energy state; however cement can no longer be dissolved. This is where precipitation begins.

Precipitation

At this point, already dissolved ions begin crystallization, which reduces the energy level of the solution as already dissolved ions begin to separate from the solution and form crystalline aggregate structures. These newly solid aggregate structures make up what are called hydration products, which differ in composition from the original grout mixture in its origin and contribute significantly to strength development. Usually, the precipitates are those of lower free energy or lower stability. This conversion from higher to lower energy is signified by the release of excess energy in the form of an exothermic (heat releasing) reaction. (The heat associated with the exothermic reaction resulting from cement hydration is known as the heat of hydration.) Now, the grout mixture is of lower energy and is no longer supersaturated, which allows dissolution to begin again.

Rate of Hydration

As the bonding nature of the crystals of the hydration contribute largely to grout strength, the rate of hydration is indicative of the strength development of a grout mixture. The rate of hydration serves as the main source of differentiation between the strength development of a typical grout mixture and a grout mixture of high replacement of cement with pozzolans. Therefore, again, it is important to understand how the rate of hydration changes over time as a grout cures.

Hydration, as measured by heat release, occurs rapidly at first. Because cement is so highly soluble, when first combined with water, reaction occurs rapidly as cement dissolves, ions are released, and heat is dissipated. This rapid reaction is short-lived, however, because the water-ionic solution, known as the pore solution, becomes very concentrated very rapidly. This high concentration physically means that cement particles become completely encompassed by the pore solution, which prevents any further dissolution. In summary, the rate of hydration begins at a peak, when a grout mix is first combined. Over the first few hours of curing, however, the rate of hydration falls to a dormant state as dissolution releases ions until the cement can no longer be penetrated by the solvent or further dissolved.

The rate of reaction increases again, usually reaching a maximum around 24 hours after mixing. This increase is due to precipitation of hydration products as previously discussed, which now allows for further dissipation. This causes a gradual decrease in reaction rate, as less and less cement is available for dissolution. The resulting state of the cementitious material consists of many unreached, unreacted cement cores or pockets. These cores are nearly difficult to breach in terms of hydration, for they are enclosed by hydration product, which have “a very fine internal porosity filled with pore solution, and larger pores called capillary cores” (Thomas & Jennings, 2008).

In order to further hydrate, one of two things must happen:

1. Water must diffuse inward through the capillary pores to reach the inner, un-reacted cement pockets and dissolve cement particles, or
2. dissolved ions from the cement cores must diffuse outward through the capillary pores to precipitate as previously discussed.

As it becomes increasingly difficult to penetrate the capillary pores in either the inward or the outward directions, the reaction rate slows at increasingly slower rates until reaching a plateau. This plateau characterizes minimal further dissolution and precipitation. It is a very slow process to arrive at this state, which is usually defined by the 28-day mark. It should, however, be noted that further dissolution and precipitation can and will occur, in either case, it will just be at relatively slow reaction rates.

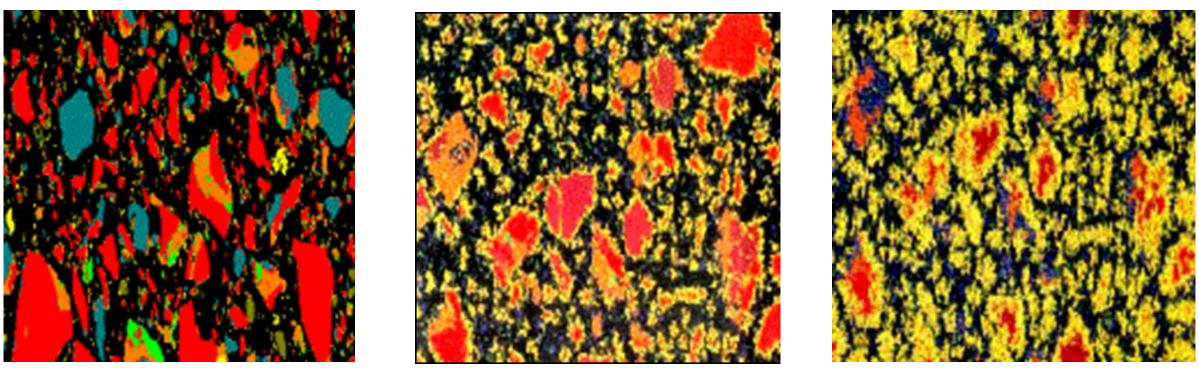
What is a pozzolan?

By definition, according to the ACI, pozzolans are metallic materials capable of forming cementitious compounds. Specifically, this is accomplished when the pozzolan reacts with calcium hydroxide and water. In grout and other cementitious construction materials, the Portland cement—a main component of which is lime, provides the calcium hydroxide. In the presence of water, lime—or calcium oxide—becomes calcium hydroxide, as represented by the following chemical equation: $CaO + H_2O = Ca(OH)_2$. By replacing some percentage of Portland cement with pozzolans and proceeding with a typical mix by adding water, the cement and water provide the means to react with the pozzolan and result in a cementitious compound. The ratio of water to cementitious materials (cement and pozzolans) is extremely sensitive when formulating self-consolidating grout mixtures. In order to achieve early strength development, the amount of water can be reduced based on the amount of cement replacement with pozzolans. However, too little water can decrease the flowability necessary for a mixture to be considered self-consolidating.

How do pozzolans work?

The activation of the pozzolans actually occurs during hydration. As cement dissolves, ions are released and when the pore solution becomes supersaturated, dissolved ions come together to form hydration products. Some of the hydration products include calcium hydroxide, abbreviated C-H and calcium silicate hydrates, abbreviated C-S-H. These hydration products are major sources of strength development within a grout mixture.

The source of these hydration products includes calcium silicates that exist as constituents of the cement, namely C_2S and C_3S (see ***Figure 1a****)*. After the cement dissolves in the water, and the pore solution becomes very highly concentrated and supersaturated, C-S-H and C-H form as products of hydration, (see ***Figure 1b, 1c, 2****)*. In accordance with the definition of pozzolans some of the calcium hydroxide is then used to activate cementitious properties in the pozzolans. This calcium hydroxide is also commonly termed “free lime”, lime that is not used toward strength. Ultimately, pozzolans redirect C-H use from strength development to cementitious activation of pozzolans. This use of C-H, is the cause of delayed strength development in grout mixtures of high cement replacement with pozzolans.



a) Unreacted Cement b) 30% Reacted Cement c) 70% Reacted Cement

Figure 1: *exhibits results of a realistic digital model of the cement hydration progression, where the colors indicate chemical composition.*

(Thomas & Jennings, 2008)

$$2C_3S + 6H = C_3S_2H_3 + \ 3\,CH$$

$$2C_2S + 4H = C_3S_2H_3 + CH$$

Figure 2: *exemplifies the hydration productions that result from the reaction between the calcium silicates (C_2S and C_3S) and water. From the reaction comes calcium silicate hydrate ($3CaO*2SiO_2*3H_2O$) abbreviated C-S-H and calcium hydroxide ($Ca[OH]_2$) abbreviated CH.*

It is predicted that free lime accounts for anywhere from 15-30% of lime produced from hydration. This means that the remaining 70-85% of lime produced from hydration is attributed to strength development. (Dunstan, 2) One must also consider that by replacing cement with pozzolans, the total amount of lime produced from hydration has already been reduced as the total amount of cement—the only reactive element in hydration—has likewise been reduced.

For example, say at an early age, about 50% of cement in a 100% cement grout mix has reacted. Assuming 20% of lime produced from hydration is free lime that serves to activate pozzolans, only 10% (100% *0.50 * 0.20) of free lime is available.

On the other hand, say at an early age, about 50% of cement in a 30% cement mixture (the remaining 70% has been made up of pozzolans) has reacted. Again, assuming 20% of lime produced from hydration is free lime that serves to activate pozzolans, only 3% (30% * 0.50 * 0.20) of free lime is available.

Thus, the replacement of cement very much affects the amount of free lime available to react pozzolans. Specifically, in the second instance, there are a lot more pozzolans and a lot less free lime available to activate them. This is representative of slowed activation of pozzolans. For this reason of reduced representation from reduced cement content combined with little free lime for pozzolanic reaction, high replacement mixtures with pozzolans don't fully develop compressive strength until much later than the 28-day strength.

Referring to the second example, the free lime that is available goes toward cementitious activation of the pozzolan as opposed to strength development. This is contrary to the first example, where there are no pozzolans to redirect use of free lime, and therefore all goes toward strength development.

It should be noted that the 20% free lime availability from cement hydration as used in the previously mentioned examples are only an assumption within an experimentally established and accepted range. Due to the variation in chemical composition of cements, the actual percent of free lime availability is variable and difficult to predict, but likely to fall within the range.

This kind of variation and overall lack of predictability is also characteristic of the pozzolans used to replace cement in this project—fly ash and blast slag.

Blast Slag

Ground granulated blast furnace slag, abbreviated in this report as “blast slag”, is a by-product of the iron and steel-making process. Blast slag is obtained via harvesting the iron slag from the blast furnace and then drying and grinding into fine powder to be used for industrial purposes.

Blast slags are usually used as direct replacements for cement on a one-to-one ratio by weight. Blast slag can be used to replace 30-85% of cement used, but 40-50% seems to be the most common industry practice.

Chemical Composition

There are four main components of blast slag:

1. CaO [Calcium Oxide] (30-50%),
2. SiO_2 [Silicon Dioxide] (28-38%),
3. Al_2O_3 [Aluminum Oxide] (8-24%), and
4. MgO [Magnesium Oxide] (1-18%).

The composition of blast slag—the proportions of each component—is highly dependent upon the parent material that the blast slag came from and thus can vary significantly. As engineers, we want high CaO content, which results in higher basicity and compressive strength when used as a supplement for grout. Higher basicity acts much like a lubricant within the grout mixture, increasing workability and improving consolidation. MgO and Al_2O_3 have similar effect on the grout mixture as CaO, but the beneficial effect caps at 10-12% and 14% respectively.

Chemical Behavior

As previously discussed in the "*How do pozzolans work?*" section, in a typical grout mixture with no blast slag added, the hydration of cement creates C-S-H (calcium silicate hydrate) and C-H (calcium hydroxide). When blast slag is added into the mixture, blast slag undergoes hydration as well to create CSH, but also creates additional CSH from pozzolanic action via combining SiO_2 from the blast slag, $Ca(OH)_2$ from the hydration process, and water to create additional CSH.

Classification

There are three grades of blast slag: grade 80, 100, and 120. These grades are categorized in accordance with ASTM C989 by their Slag Activity Index, which is determined by taking a ratio of the average compressive strength of a mixture with blast slag and a mixture without blast slag:

$$Slag\ Activity\ Index.\% = \frac{SP}{P} * 100$$

SP: average compressive strength of a concrete mixture with blast slag substituting up to 50% of cement, by weight

P: average compressive strength of a control group concrete mixture without any blast slag substitution

ASTM C989 standard also requires satisfaction of further specification of the test specimens regarding mixture proportions (see ***Figure 3***). These include:

1. No more than 80% of mixture passes through a No. 325 sieve
2. Air content in the mixture be less than 12%
3. Sulfur and ion sulfate content be less than 2.5% and 4.0%, respectively.

Concrete mix with grade 120 blast slag will result in equivalent or greater compressive strength on the 7-day test than the 28-day compressive strength of the controlled concrete mix (see ***Figure 3***). Mixture with grade 100 blast slag will generally result in an equivalent or greater compressive strength on the 28-day test than the 28-day compressive strength of the controlled concrete mix. Concrete mixture with grade 80 blast slag will always result in a lower compressive strength than the controlled concrete mixture, but it emits significantly less heat from the hydration process. Blast slag with grade 100 or greater is recommended for any concrete mixture, unless specific conditions call for grade 80 blast slag.

TABLE 1 Physical Requirements

Item		
Fineness:		
amount retained when wet screened on a 45-μm (No. 325) sieve, max %		20
Specific surface by air permeability, Test Method C 204 shall be determined and reported although no limits are required.		...
Air Content of Slag Mortar, max %		12
	Average of Last Five Consecutive Samples	Any Individual Sample
Slag Activity Index, min, %		
7-Day Index		
Grade 80	...	...
Grade 100	75	70
Grade 120	95	90
28-Day Index		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	110

Figure 3: *ASTM C989 Blast Slag Requirements*

Structural Application

Blast slag has multiple structural uses for a concrete mixture, some of which are as follows:

1. Blast slag increases the durability of the concrete. Previous studies show that concrete mixed with blast slag continuously gain strength over longer period of time. A control concrete mixture without blast slag would reach the cap compressive strength of about 130% 28-day strength at about two years after the mixture has been set. On the other hand, a concrete mixture with blast slag has shown to continuously gain strength over ten to twelve years, reaching the max compressive strength of about 200% 28-day strength.

2. Concrete mixtures with blast slag set slower than the controlled concrete mixtures, taking longer to reach the "28-day strength." This attribute, while often thought of as a flaw, can actually be used as an advantage. Because a concrete mixture with blast slag will set slower than a controlled concrete mixture, a blast slag mixture can help prevent cold joint formations.

3. Blast slag mixtures exhibit a considerably lower heat of hydration than their controlled concrete mixture counterparts. Not only can blast slag be used to prevent flash setting, but blast slag can also be used in high volume concrete pour situations to prevent explosive blowout situations. For example, in constructing a concrete dam, the heat of

hydration can get so high as to increase the internal pressure enough to cause concrete blowout via explosive decompression. This is likewise applicable to high volume grout pour scenarios.

4. Due to the fine particle size that is characteristic of blast slag—a particle size that is significantly smaller than that of cement particle—blast slag mixtures typically have higher resistance to chloride ingress, which ultimately results in reduced rebar corrosion in long term usage. The lower permeability resulting from fine particle size could also suggest the possibility of smaller cover requirements in concrete applications. Finally, and perhaps most importantly, smaller particle size creates a tighter bond between the blast slag, cement, and the aggregates, ultimately leading to increased flexural strength of the grout.

5. Blast slag mixtures have shown higher resistance to sulfate attacks from the ground and seawater.

Non-Structural Applications

Aside from structural applications, replacement of cement with blast slag serves other non-structural applications as well. Some of these are as follows:

1. Blast slag concrete mixtures produce a fairer, whiter color, which is often more desirable to architects.
2. Due to the fine particle sizes, blast slag concrete mixtures produce smoother and relatively blemish free surface. Not only is the finer surface more aesthetically pleasing, but the smooth surface also deters dirt from adhering, ultimately leading to reduced maintenance cost.
3. Blast slag also helps preventing efflorescence in concrete members.

Fly Ash

Fly ash is a by-product of coal combustion, during which, finer particles that rise with other flue gases can be caught by use of particle filtration equipment. These particles make up what is known as fly ash, the composition of which varies significantly on the basis of the source of the coal. When used alone to replace cement in a grout mixture, fly ash is usually used to replace between 15 and 25 percent of cement, which is similar to the mixes that were used in this project.

Chemical Composition

The chemical composition of any fly ash is largely dependent upon the coal that was combusted to create the fly ash. In fact, classification is largely defined by the parent material used to create fly ash. Specifically, there are two classes—Class F (bituminous coal) and Class C (sub-bituminous coal). For this project, class F fly ash was used, from here on any reference to fly ash will be specific to Class F fly ash.

While the composition varies, every Class F fly ash consistently contains high amounts of silicon oxide and aluminum oxide, characteristic of any pozzolan composition. There are four main components that make up most fly ashes.

1. SiO_2 [Silicon Dioxide] (30-60%)
2. Al_2O_3[Aluminum Oxide] (15-35%)
3. Fe_2O_3[Iron (III) Oxide] (5-20%)
4. CaO [Calcium Oxide] (1-25%)

Also common amongst type F fly ashes, but at much smaller percentages, are MgO [Magnesium Oxide], Na_2O [Sodium Oxide] , K_2O [Potassium Oxide], and SO_3 [Sulfur Trioxide].

Chemical Behavior

Partial replacement of cement with fly ash yields the hydration processes, however, occurs at slower rates of hydration. This occurs as a result of many different potential sources. Decreased cement use—as a result of replacement—reduces the amount of available free lime which is used to activate cementitious properties of pozzolans. Also, by definition, pozzolanic materials require calcium hydroxide to activate cementitious properties, which actually slows the precipitation aspect of hydration.

To supplement the hydration process, it has also been shown that due to particle formation properties of fly ash, hydration of low-calcium fly ash in grout often involves hydration of siliceous glass on much of the fly ash particle surfaces as well as Al_2O_3 and Fe_2O_3 components. In turn, calcium hydroxide products decrease, while calcium silicate hydrates produced increase. Reduction of calcium hydroxide products directly relates to the delayed strength development characteristic of cement replacement with fly ash. Increased calcium sulfate hydrates products directly relates to the potential for much higher compressive strengths, past the 28-day mark, which is similarly characteristic of cement replacement with fly ash.

Particle Size, Distribution, and State

It is important to note that reactivity of fly ash is very strongly correlated with particle size and distribution, as well as the physical state of said particles.

Variation of particle size of fly ashes can be summarized as follows:

1. A particle size of less than 20 micrometers typically translates to a particle structure known as a plerosphere or a hollow sphere containing smaller spheres. These particles are typically granular and porous in terms of texture.
2. A particle size between 20 and 50 micrometers typically translates to an oval shaped and pale colored--not transparent—particle.
3. A particle size of greater than 50 micrometers typically translates to a more rough, pebble sized, porous particle. These particles are mostly white but can be black and glassy as well. They are usually thin-shelled and brittle.

Just as grain-size distribution in a grout affects the flowability and segregation of a grout mix, the grain-size distribution of a fly ash likewise significantly influences the reactivity of said fly ash. In terms of distribution, the particles that make up a fly ash are mostly smooth, solid, and spherically shaped particles although some can be rough and hollow. Hollow spheres, known as cenospheres, have been found to react very quickly.

The remainder of particles may be partially rounded and may contain pockets or unburned coal fragments. It, too, is common to find fine powders of various chemical makeups—mostly sulfates—along the surface of the particles. These sulfates are very soluble and quick to hydrate as well.

Classification

Classification of fly ashes, as defined by ASTM C 618, is done on the basis of chemical composition. This variation in chemical composition is rooted in the parent material—the coal combusted to create the fly ash. Thus, two classes have been established: Class C and Class F.

Class C

Class C fly ash is the resultant of sub-bituminous coal or lignite combustion. It contains much higher percentages of calcium oxide in comparison to its counter as well as glass particle structure. For these reasons, it too is known to be more reactive and thus has a higher heat of hydration associated with its use as a pozzolan. However, this higher reactivity leads to increased retardation of early strength development in comparison to Class F fly ash.

Class F

Class F fly ash is the resultant of bituminous coal or anthracite combustion. Lower percentages of calcium oxide is characteristic of Class F fly ash, as can be seen in the "*Chemical Composition*" section, in which, typical percentages of chemical composition for Type F fly ash—which was used in this project, Class F fly ash tends to be less reactive, has a lower heat of hydration, and decreased retardation of early strength development.

ASTM 618 differentiates between Class F and Class C fly ash mainly on the basis of SiO_2+Al2O_3 + Fe2O_3 (silicon dioxide + aluminum oxide + iron oxide) content. Being that CaO (calcium oxide) as well as the three previously listed chemicals are the main components of fly ash, this type of classification is related to the CaO (calcium oxide) content percentage. The ASTM also lists physical requirements in terms of fineness, strength activity index, soundness, and uniformity. Some of the ASTM specifications are listed on the following page (see ***Figure 4***).

TABLE 1 Chemical Requirements

	Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min,%	70.0	70.0	50.0
Sulfur trioxide (SO_3), max,%	4.0	5.0	5.0
Moisture content, max,%	3.0	3.0	3.0
Loss on ignition, max,%	10.0	6.0[A]	6.0

[A] The use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

TABLE 2 Physical Requirements

	Class		
	N	F	C
Fineness:			
Amount retained when wet-sieved on 45 µm (No. 325) sieve, max,%	34	34	34
Strength activity index:[A]			
With portland cement, at 7 days, min, percent of control	75[B]	75[B]	75[B]
With portland cement, at 28 days, min, percent of control	75[B]	75[B]	75[B]
Water requirement, max, percent of control	115	105	105
Soundness:[C]			
Autoclave expansion or contraction, max,%	0.8	0.8	0.8
Uniformity requirements:			
The density and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than:			
Density, max variation from average,%	5	5	5
Percent retained on 45-µm (No. 325), max variation, percentage points from average	5	5	5

[A]The *strength* activity index with portland cement is not to be considered a measure of the compressive strength of concrete containing the fly ash or natural pozzolan. The mass of fly ash or natural pozzolan specified for the test to determine the *strength* activity index with portland cement is not considered to be the proportion recommended for the concrete to be used in the work. The optimum amount of fly ash or natural pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing. *Strength* activity index with portland cement is a measure of reactivity with a given cement and is subject to variation depending on the source of both the fly ash or natural pozzolan and the cement.
[B]Meeting the 7 day or 28 day *strength* activity index will indicate specification compliance.
[C]If the fly ash or natural pozzolan will constitute more than 20% by mass of the cementitious material in the project mixture, the test specimens for autoclave expansion shall contain that anticipated percentage. Excessive autoclave expansion is highly significant in cases where water to cementitious material ratios are low, for example, in block or shotcrete mixtures.

Figure 4: *ASTM 618 Fly Ash Requirements*

Structural Application:

Partial substitution of cement with fly ash in structural application has been proven to serve many beneficial purposes. Some of these are as follows:

1. Due to pozzolanic properties inherent of fly ash, replacement of cement with fly ash allows decreased water to cementitious materials ratios which ultimately produces grout mixture designs of similar compressive strength and improved workability compared to traditional, non-self-consolidating grout mixtures. This mitigates flow through congested masonry cells and eases uniform, homogenous consolidation.

2. Similarly, as a result of pozzolanic properties of fly ash, replacement of cement with fly ash allows for decreased water to cementitious materials ratios by decreasing the necessary water while also increasing the total volume of cementitious materials. This reduces the potential for bleeding and segregation that can be detrimental to strength development and consolidation.

3. Most importantly, replacement of cement with fly ash has been proven to increase the long term strength and modulus of elasticity of grout mix designs. This is accomplished via reduction of water content alongside the increased volume of cementitious materials in the mixture—which results from pozzolanic activation. To supplement this, the fine particle size of fly ash yields potential for improved

consolidation, which is likewise beneficial to long term strength development past the 28-day mark. In fact, in many studies, grout mixtures with partial replacement of cement with fly ash have proven to surpass the compressive strength capacities of many 100% cement mixtures given sufficient time. But the compressive strength in this context is not only dependent on replacement percentage, but also pozzolan reactivity, grading of pozzolans and aggregates, water content, and curing conditions.

4. Specifically, the use of Class F fly ash for cement replacement has been proven to reduce the heat of hydration of a mix design. This is significant especially with respect to massive concrete structures, where the heat of hydration can get so high that the concrete can expand, cool non-uniformly, induce stresses in the partially cooled concrete, and crack prematurely.

5. As a result of the increased volume of paste, attributed to pozzolanic reaction of fly ash, eased consolidation and thus reduced permeability is a common benefits of cement replacement with fly ash. Reduced permeability, in turn, creates a more impervious grout mixture which improves corrosion resistance and resistance to chemical attack with less (if any) need for admixtures. In either case—less or no need for admixtures—resistance to corrosion and chemical attack is achieved in a more cost effective way.

6. Increased flowability as well as increased volume of cementitious materials may improve mixture cohesiveness. This allows for better bonds to be made between compressive and tensile members of masonry elements and also increases pumpability, which eases the construction process in terms of time and money.

Non-Structural Application

Partial replacement of cement with fly ash has also proven value in some architectural application, as follows:

1. Fly ash pozzolanic reactions provide extra cementitious value and decrease the water demand. As previously discussed, this decreases permeability and thus reduces potential for damage pertaining to corrosion, deterioration, shrinking, and cracking. Use of fly ash in grout mixes thus contributes to maintaining aesthetic value.
2. When architectural finish are important, the use of fly ash in concrete rather than grout, fly ash is once again beneficial in that aesthetically, it creates a more favorable finish color and texture as a result of the small particle size.
3. Lastly, by pozzolanic nature, fly ash provides extra cementitious value which, along with decrease water content, produces less voids and a reduces appearance of efflorescence—a type of salt deposit that forms on the surface of cementitious structural materials. This is beneficial in

terms of aesthetic and surface treatments and finishes, which adhere more efficiently in the absence of efflorescence.

<u>Testing and Experiment:</u>

In order to compare the strength of self-consolidating grout design mixtures with known values, compressive strength tests were conducted on individually grouted specimens at 7-day and 28-day curing times per ASTM C 1019. The first experiment (see ***Compression Testing***) was used to specify a grout design mixture to serve as the experimental unit for the second experiment (see ***Consolidation***), based on strength and water content. The construction of the reinforced masonry wall (4’ wide by 12’ high) was required to investigate the consolidation of the selected grout design mixture after a 56-day curing period.

Tests for both experiments were performed at the High Bay Laboratory and Concrete Laboratory. Both laboratories are located in the Architectural Engineering Department of the College of Architecture and Environmental Design at the California Polytechnic State University, San Luis Obispo Campus in California.

Grout Mixture Sampling

Material Preparation

Materials used in the experiments include the following:

Portland cement Type II

Coal Fly Ash Type F

Ground granulated blast furnace slag (GGFBS) Grade 120

Type N masonry mortar

Hollow concrete masonry units (CMU)

8x8x16 H-block / 8x8x16 Open End / 8x8x8 Half-block

Coarse aggregate (3/8" pear gravel)

Fine aggregate (washed concrete sand)

#5 Rebar (horizontal and vertical)

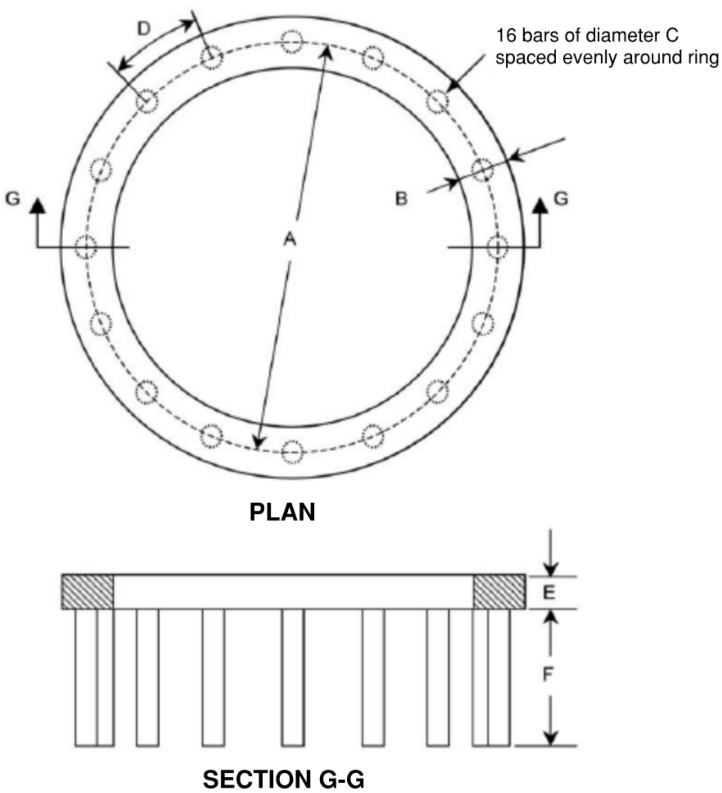
Potable water

Testing Surface

The testing measuring gage was made with a 5/8" board of plywood and a thin sheet of steel for the flow surface. The plywood board acted as a rigid base. The nonabsorbent steel surface was in compliance with ASTM C 1611. A 36" diameter circle was traced around the bull's-eye. The testing surface was kept out of direct sunlight to prevent the steel base plate from conducting heat. For testing, the surface was leveled and wiped down removing any standing water.

J-Ring

The J-Ring was constructed using a 1" thick steel plate and 5/8" diameter smooth steel rods. The ring required a 12" diameter measured from the center with an extra inch added for thickness. Holes were made equidistant around the centerline of the ring. The steel rods were cut in the shop, making sixteen 4-inch bars (see ***Figure 5*** for all dimensional tolerances).



Dimension	in	mm
A	12.0 ± 0.13	300 ± 3.3
B	1.5 ± 0.06	38 ± 1.5
C	0.625 ± 0.13	16 ± 3.3
D	2.36 ± 0.06	58.9 ± 1.5
E	1.0 ± 0.06	25 ± 1.5
F	4.0 ± 0.06	200 ± 1.5

Figure 5: *Dimensional tolerances when constructing the J-Ring apparatus per ASTM C 1621.*

Once the ring was cut out, the steel bars were spot-welded using the weld station in the CAED shop (see ***Figure 6b***). The bars were sawed on the bottom to ensure the J-Ring sits level during testing (see ***Figure 6c***).

Figure 6: *J-ring construction*

Mix Proportioning

Thirteen total mix designs were compiled; initial designs were based off Bateman's Report (Bateman, 2014) with remaining designs based on independent research. **Table 1.1** is representative of the mix designs based on Bateman's research. Test names were assigned based on cement replacement and material (take 70SF for example, "70" means 70% cement replacement, "S" means blast slag was used, and "F" means fly ash was used). In order to achieve flowability without delaying early strength development, water content was reduced and modified for each mix design. A baseline mix design having a water to cementitious ratio of 1.375 was used matching the 70SF test from Bateman's Report; the 70SF test yielded the best results with a slump of 26", a VSI of 1, and a 28-day compressive strength of 1900 psi (Bateman, 2014).

Type F Fly Ash and GGBFS Replacements			
Test Name	Cementitious Material		
	Cement (% Vol.)	Fly Ash (% Vol.)	GGBFS (% Vol.)
50F	50	50	0
60F	40	60	0
70F	30	70	0
60SF	40	15	45
70SF	30	17.5	52.5
80SF	20	20	60
100C	100	0	0

Table 1.1 Percentage of cementitious material based on design mixtures from Bateman Report

Procedure

Batches were mixed in accordance with ASTM C 476 using the mechanical mixer located in the Concrete Yard (see ***Figure 7a***). The freshly mixed grout was transported to the Concrete Lab in a wheelbarrow and poured into pre-assembled molds to create compressive test specimens. The remaining grout was remixed and used for slump tests. The slump flow test was performed first in accordance with ASTM C 1611, using an inverted mold configuration (see ***Figure 7b***). With the mold centered on the bull's-eye, grout was poured in one lift without tamping or vibration. Raising the mold vertically, the grout was allowed to spread on the test surface and the slump flow was determined by taking the average of two measured diameters (see ***Figure 7c***).

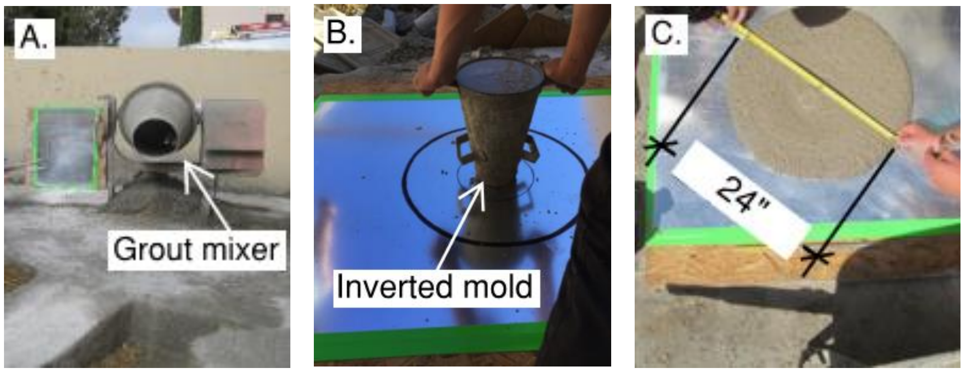


Figure 7: *Procedures for sampling grout mixtures.*

A Visual Stability Index value was assigned after every test (determined by Appendix XI of ASTM C 1611) to ensure each mix was homogeneous. Values were assigned based on observing segregation of aggregates along the perimeter, and any cases of bleeding or haloing (see ***Figure 8a***). If the slump test yielded a slump flow between 24 and 30 inches, the mixture was remixed and used again for the passing ability test; the passing ability of the grout was determined following the same procedure as the slump test, the only difference being the incorporation of the J-Ring in combination with the slump mold (see ***Figure 8b***). The same process used to determine slump flow was repeated to determine the "J-Ring" flow. The difference calculated between slump flow and J-Ring flow represented the passing ability of the grout, which is defined as the ability of self-consolidating grout to flow under its own weight (without vibration). A blocking assessment was also performed to assess the consolidation around the bars of the J-Ring (see ***Figure 8c***).

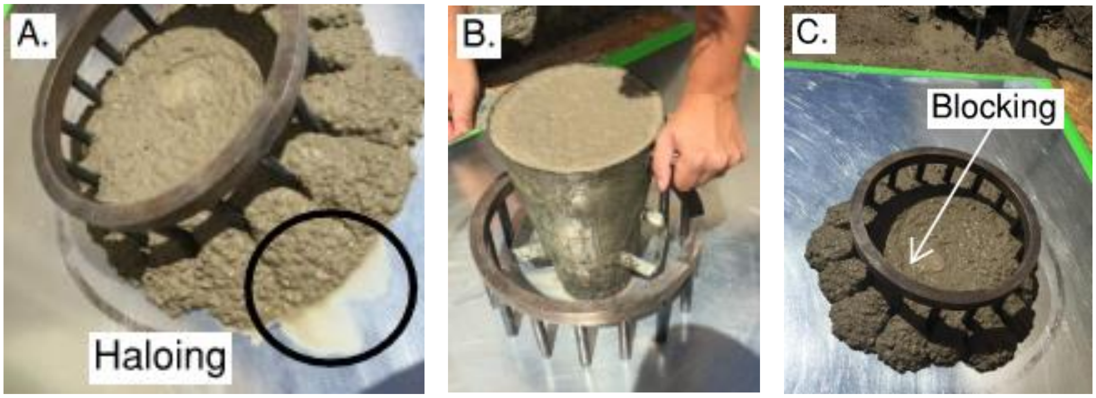


Figure 8: *Procedure for sampling grout mixtures (continued).*

Mix Designs

Grout batches were prepared for each grout mixture listed in **Table 1.2** and **Table 1.3**. Proportions were initially measured by volume, however when test results did not match baseline results, proportions were measured by weight and recorded for future reference; grout mixtures measured by volume do not have weights recorded in **Table 1.2**.

Mix Name	Cement % Vol.	Fly Ash % Vol.	Blast Slag % Vol.	Aggregates (lbs.)		Water/Cementitious Materials Ratio
				Fine	Coarse	
70SF1	30.0	17.5	52.5	N/A	N/A	1.375
70SF2	30.0	20.0	50.0	31	35	1.2
70SF3	30.0	23.0	47.0	N/A	N/A	1.25
70SF4	30.0	25.0	45.0	38	20	1.25
70SF5	30.0	25.0	45.0	46	17	1.25
70SF6	30.0	25.0	45.0	44	16	1.25

Table 1.2 Proportions used in mix designs tested on day 1 of sampling

Mix Name	Cement % Vol.	Fly Ash % Vol.	Blast Slag % Vol.	Aggregates, parts Fine	Aggregates, parts Coarse	Water/Cementitious Materials Ratio
70SF7	33.6	24.6	41.8	2.25	1.00	1.08
	(4.5 lbs.)	(3.3 lbs.)	(5.6 lbs.)	(48.7 lbs.)	(17.8 lbs.)	14.39
70SF8	37.2	22.8	40.0	2.25	1.00	1.21
	(5.4 lbs.)	(3.3 lbs.)	(5.8 lbs.)	(48.3 lbs.)	(17.4 lbs.)	17.55
70SF9	37.7	22.6	39.7	2.25	1.00	1.21
	(5.5 lbs.)	(3.3 lbs.)	(5.8 lbs.)	(46.0 lbs.)	(17.0 lbs.)	17.64
70SF10	37.4	17.0	45.6	2.25	1.10	1.22
	(5.5 lbs.)	(2.5 lbs.)	(6.7 lbs.)	(46.0 lbs.)	(18.8 lbs.)	18.00
75SF1	36.2	16.4	47.4	2.25	1.10	1.09
	(5.5 lbs.)	(2.5 lbs.)	(7.2 lbs.)	(45.0 lbs.)	(19.0 lbs.)	16.60
75SF2	36.2	16.4	47.4	2.25	1.10	1.09
	(5.5 lbs.)	(2.5 lbs.)	(7.2 lbs.)	(45.0 lbs.)	(19.0 lbs.)	16.60
65SF1	43.9	16.9	39.2	2.50	1.10	1.11
	(6.5 lbs.)	(2.5 lbs.)	(5.8 lbs.)	(50.6 lbs.)	(19.0 lbs.)	16.50

Table 1.3 Proportions used in mix designs tested on day 2 of sampling

During sampling, discrepancies among results lead to further investigation in the preparation of grout batches. Despite issues of proportioning as noted earlier, tested grout mixtures were still considerably more viscous even after measuring proportions by weight. One issue was with the quality of fly ash; the fly ash had hardened, creating insoluble clumps when mixed. Samples tested on day 2 were performed with sieved fly ash as noted in **Table 1.3**. To improve consistency between tests, fly ash was sieved through a number 16 (see **Figure 9**).

To compare strengths of final self-consolidating design mixture used in grouting of the wall (see ***Appendix A*** for basis on selecting favorable self-consolidating design mixture) with conventional grout strengths, a 100% cement mixture was sampled for 7-day and 28-day compression tests. The proportions used in the 100% cement mixture are listed in **Table 1.4**

Figure 9: *Sieve analysis of fly ash.*

To compare strengths of final self-consolidating design mixture used in grouting of the wall (see ***Appendix X*** for basis on selecting favorable self-consolidating design mixture) with conventional grout strengths, a 100% cement mixture was sampled for 7-day and 28-day compression tests. The proportions used in the 100% cement mixture are listed in **Table 1.4**

Mix	Cement	Fly Ash	Blast Slag	Aggregates, parts		Water/Cementitious
Name	% Vol.	% Vol.	% Vol.	Fine	Coarse	Materials Ratio
70SF8	100.0	0.0	0.0	2.25	1.00	0.88
100%	(16.4 lbs.)	(0.0 lbs.)	(0.0 lbs.)	(50.4 lbs.)	(17.0 lbs.)	14.39

Table 1.4 Proportions used in 100% cement mix design

Compression Testing

Curing

Test specimens were prepared by pouring grout into cores of 8x8x16 CMU blocks; CMU blocks of same type and moisture contents as those used for construction of the wall were used to simulate in-situ conditions. Before pouring, molds were prepared in the Concrete Lab by placing CMU blocks on top of a layer of cardboard. The blocks were placed inside trash bags to protect the specimens from rapid evaporation and contamination during curing. Once poured, specimens were covered and left undisturbed for 24 hours. Inside the curing room, plywood boards were placed on top of tubs to accommodate space for 7-day and 28-day compression test specimens. In accordance with ASTM C 1019, a maximum-minimum thermometer was placed in the curing room to track the temperature and humidity experienced during curing.

Preparation

On testing days, specimens were cut from the CMU blocks using the diamond blade wet saw inside the Concrete Lab. Compression test specimens were measured and recorded to satisfy the dimensional requirements of ASTM C 1019 (see ***Figure 10a***).

Capping

Alternative methods were found in compliance with ASTM C 617 used hydro-stone, providing an alternative to lack-of conventional sulfur caps. Metal plates were used to create level testing surfaces (see ***Figure 10b***). Once the hydro-stone dried, the plates were removed resulting in the surface (see ***Figure 10c***).

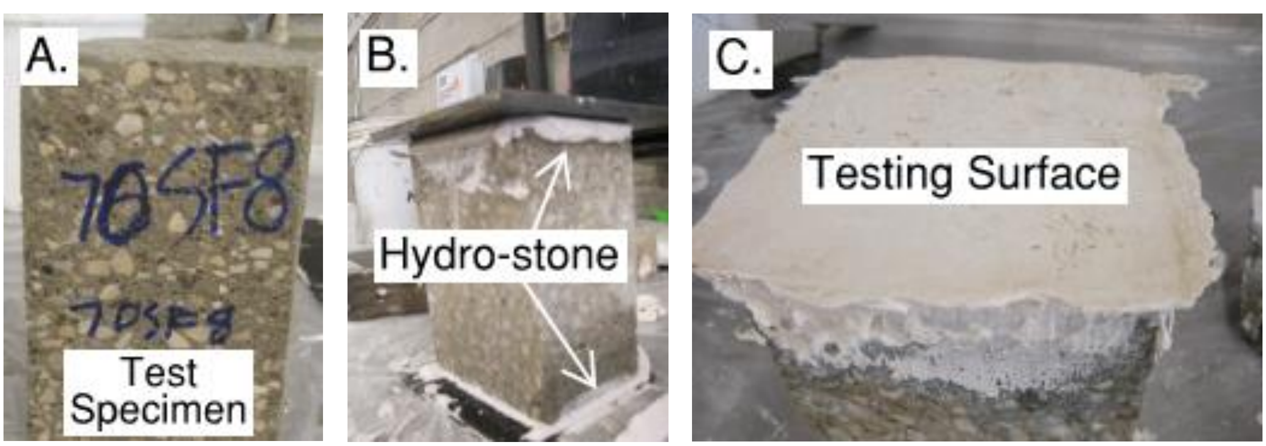


Figure 10: *Preparation of test specimens per ASTM C 617.*

Loading/Breaking

Once specimens were capped, 7-day and 28-day compression tests were tested in accordance with ASTM C 1019 (see ***Figure 11b***). A schedule was maintained in order to record unforeseen issues encountered during testing. An oil leak in the compression test machine occurred after 7-day compression tested were performed and recorded. The leak remained an issue for the 28-day compression tests, requiring the assistance of the lab manager in order to compensate for the loss of oil experienced during testing. For the duration of the 28-day compressions tests, the machine was kept lubricated in order to obtain accurate test results.

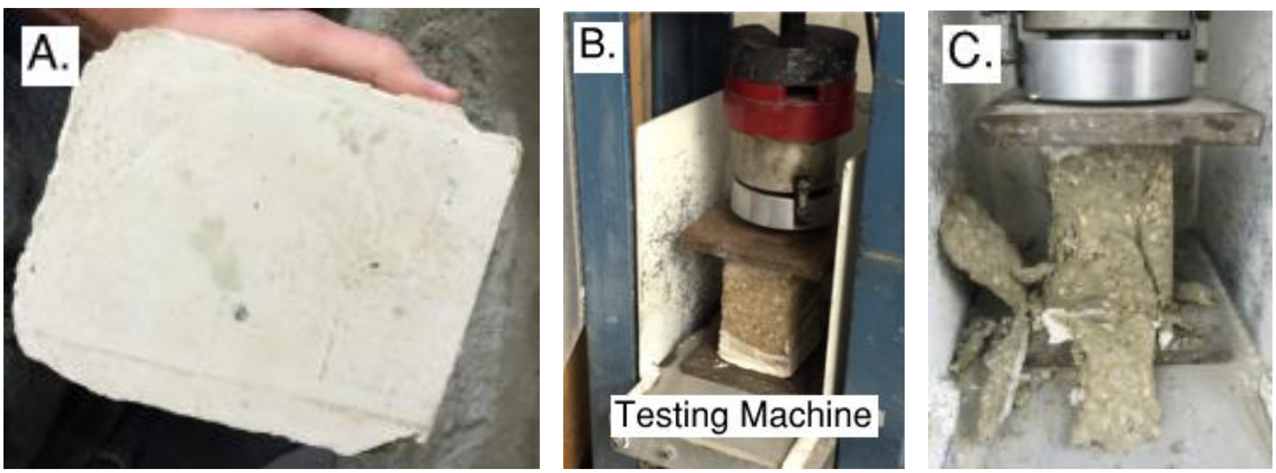


Figure 11: *Compression testing*

Recording

For each specimen tested, maximum strengths were recorded to calculate compressive strengths. Failure modes were also assessed and recorded. **Table 1.5a** and **Table 1.5b** list the results for the 7-day and 28-day compressions tests for the test specimens prepared on day 1 of sampling. **Table 1.6a** and **Table 1.6b** list the results for the 7-day and 28-day compressions tests for the test specimens prepared on day 2 of sampling.

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF1	4.75	5.625	7.5	7.5	7	25000	935.7	Conical Failure	8x8x16	1
70SF2	4.75	5.625	7.625	7.625	7	32000	1197.7	Conical Failure	8x8x16	1
70SF3	4.75	6	5.375	5.25	7	28000	982.5	Shear Failure	8x8x16	1
70SF4	4.4375	5.6875	7.4375	7.375	7	33000	1307.5	Shear Failure	8x8x16	1
70SF5	4.625	5.75	7.5	7.4375	7	33500	1259.7	Conical Failure	8x8x16	1
70SF6	4.75	5.1875	3.125	3.1875	7	27000	1095.8	Conical Failure	8x8x16	1

Table 1.5a Maximum strengths, compressive strengths, and failure modes for 7-day test specimens prepared on day 1 of sampling

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF1	4.625	5	7.375	7.5	28	35000	1514	Conical	8x8x16	1
70SF2	4.625	5.625	7.375	7.5	28	45000	1730	Conical	8x8x16	1
70SF3	4.875	5.5	7.625	7.5	28	32000	1193	Columnar	8x8x16	1
70SF4	4.625	5.75	7.5	7.5	28	45000	1692	Shear	8x8x16	1
70SF5	4.75	5.625	7.625	7.5	28	51000	1909	Shear	8x8x16	1
70SF6	4.625	5	7.5	7.5	28	38000	1643	Columnar	8x8x16	1

Table 1.5b Maximum strengths, compressive strengths, and failure modes for 28-day test specimens prepared on day 1 of sampling

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF7	4.5	5.375	7.625	7.625	7	34000	1405.7	Conical Failure	8x8x16	1
70SF8	5.0625	4.625	7.5	7.5	7	33000	1409.4	Conical Failure	8x8x16	1
70SF9	3.875	5.75	7.375	7.5	7	28000	1256.7	Shear Failure	8x8x16	1
70SF10	4.5	4.75	7.375	7.5	7	33000	1543.9	Conical Failure	8x8x16	1
75SF1	5.375	4.75	7.5	7.5	7	51000	1997.6	Conical Failure	8x8x16	1
75SF2	4.625	4.75	7.5	7.5	7	26000	1183.5	Conical Failure	8x8x16	1
65SF1	4.75	5.125	7.625	7.5	7	19000	780.5	Conical Failure	8x8x16	1
100C	4.75	5.25	7.5625	7.5	7	70750	2837.1	Shear Failure	8x8x16	1

Table 1.6a Maximum strengths, compressive strengths, and failure modes for 7-day test specimens prepared on day 2 of sampling

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF7	4.6875	5.3125	7.375	7.4375	28	47000	1887	Shear	8x8x16	1
70SF8	4.75	5.25	7.625	7.625	28	35500	1424	Shear	8x8x16	1
70SF9	4.6875	5.5625	7.5625	7.5	28	57000	2186	Shear	8x8x16	1
70SF10	4.6875	5.25	7.375	7.4375	28	54500	2215	Conical	8x8x16	1
75SF1	4.6875	5.375	7.5625	7.375	28	76000	3016	Shear	8x8x16	1
75SF2	4.6875	5.5	7.375	7.375	28	56500	2192	Shear	8x8x16	1
65SF1	4.8125	5.4375	7.5	7.5	28	44000	1681	Shear	8x8x16	1

Table 1.6b Maximum strengths, compressive strengths, and failure modes for 28-day test specimens prepared on day 2 of sampling

Consolidation

Preparation

Before the wall was constructed, the construction manager of the project was in charge of compiling a material take off list to ensure enough materials would be available and schedule deadlines would be satisfied; the purchasing of blast slag was also taken into consideration due to limited availability in San Luis Obispo. **Table 1.7** provides the final material and equipment estimate for the construction and grouting of the wall.

Materials and Equipment Estimate for CMU Wall				
Description	Quantity	Units	Equipment Unit Cost	Materials Unit Cost
Hollow Concrete Masonry Units (CMU)	63	Each		
8x8x16 Standard H-Block CMU	27	Each		$ 1.05
8x8x16 Open End CMU	18	Each		$ 1.05
8x8x8 Half-Block CMU	18	Each		$ 1.05
#5 Rebar (Horizontal and Vertical)	7	20' Bars		$ 9.87
Rebar Ties	1	100 count bag		$ 2.48
Self Consolidating Grout Mix (Total)	13	CF		
Portland Cement Type II (.78 CF)	2	94 # Sacks		$ 13.77
*Coal Fly Ash Type F (0.65 CF)	88	lbs		$ 0.02
**Ground Granulated Blast Furnace Slag (GGBFS) Grade 120 (1.08 CF)	92	lbs		$ 0.028
Coarse Aggregate (3/8 in.) Pea Gravel (5.37 CF)	11	0.5 CF Sacks		$ 7.19
Fine Aggregate Washed Concrete Sand (2.38 CF)	6	50 # Sacks		$ 4.79
Potable Water	2.86	CF		
Mortar Mix	4	60 # Sacks		4.54
Scaffolding	1	Each	$ 100.04	

Table 1.7 Materials and Equipment Estimate for CMU Wall

The lab manager provided assistance in order to prepare a spot in the High Bay Lab for construction. Large steel beams were unbolted and set in place accordingly for bracing (see ***Figure 12b*** for beam placement). A baseplate was needed to act as a nonabsorbent membrane between the wall and the floor. A plywood board matching the width and thickness of the wall was used; the board was placed on the floor to prevent bonding during grouting. The plywood baseplate was not anchored into the floor; the first course of vertical rebar was anchored into the plywood base during construction.

For the bracing, 2x4 boards of dimensional lumber were clamped to the steel beam behind the wall, at a height of 9’ from the ground (see ***Figure 12a***). Additional 2x4 boards were drilled into the clamped boards, spanning along the width of the wall (see ***Figure 12b***). Sheets of OSB were clamped together at the top of the wall to distribute forces from the two front braces. The braces were made using 2x4 boards of dimensional lumber; the top angle was cut with a handsaw and could be adjusted by unbolting the steel beam on the ground. Clean outs and saddles were also prepared to accommodate the placement of the horizontal rebar (see ***Figure 13*** for rebar placement). Open-End CMU blocks were gently hammered to create saddles (see ***Figure 12c***). Clean outs were made using a diamond blade wet saw.

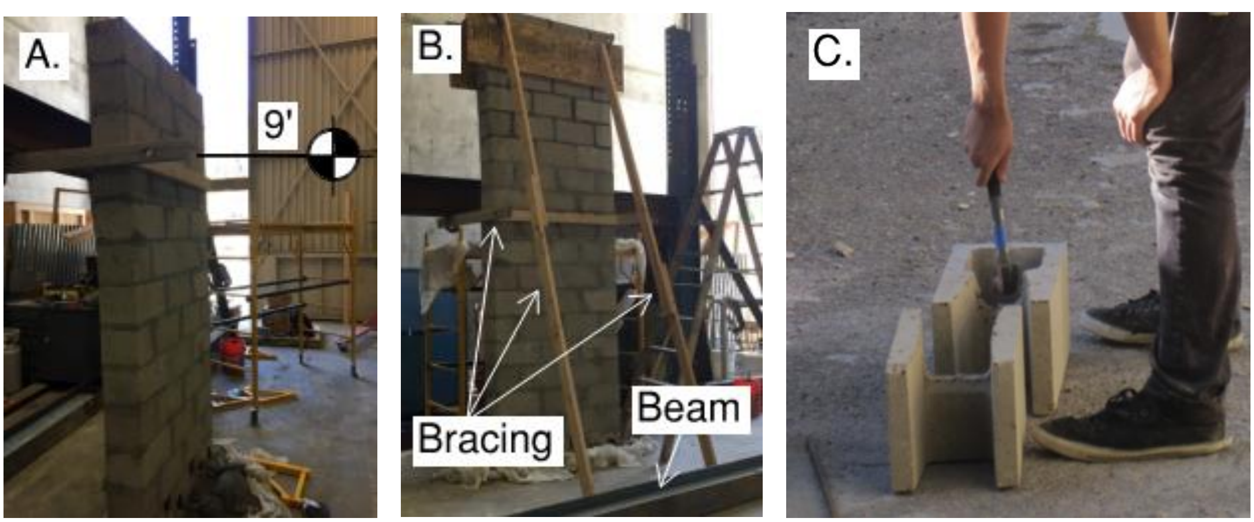


Figure 12: *Wall construction*

Issues arose during preparation, pushing the completion date of the wall back a few weeks. Having an 11-week timeframe to perform a design-build project left little time to hire a professional mason once materials were available to construct the wall. Scaffolding availability was also an issue; availability was limited in the area, leaving little room for flexibility in schedule changes.

Wall Construction

The wall was constructed in an indoor facility, free from exposure to direct sunlight and other weather conditions that could alter the curing process. Bags of mortar mix were mixed in the mechanical mixer (see ***Figure 7a***) and transported in a wheelbarrow to the High Bay Laboratory. Duties were facilitated as follows:

- One person was in charge of mixing the mortar; constant attention was required due to warm weather experienced during construction.
- One person was in charge of preparing rows of CMU blocks in the correct order of construction; Open-End blocks that were cut were required at horizontal rebar locations (see ***Figure 13***).
- One person was in charge of applying mortar joints on the CMU blocks, passing them to the builder when needed.
- One person was in charge of building the wall; mortar joints were inspected and leveled for each row of block placed.

The wall was built in one lift, using rebar ties to attach horizontal and vertical bars every 16” on center (see ***Figure 12*** for as-built elevation). Once completed, the wall was left undisturbed until ready to grout. (See ***Figure 13*** for the construction process).

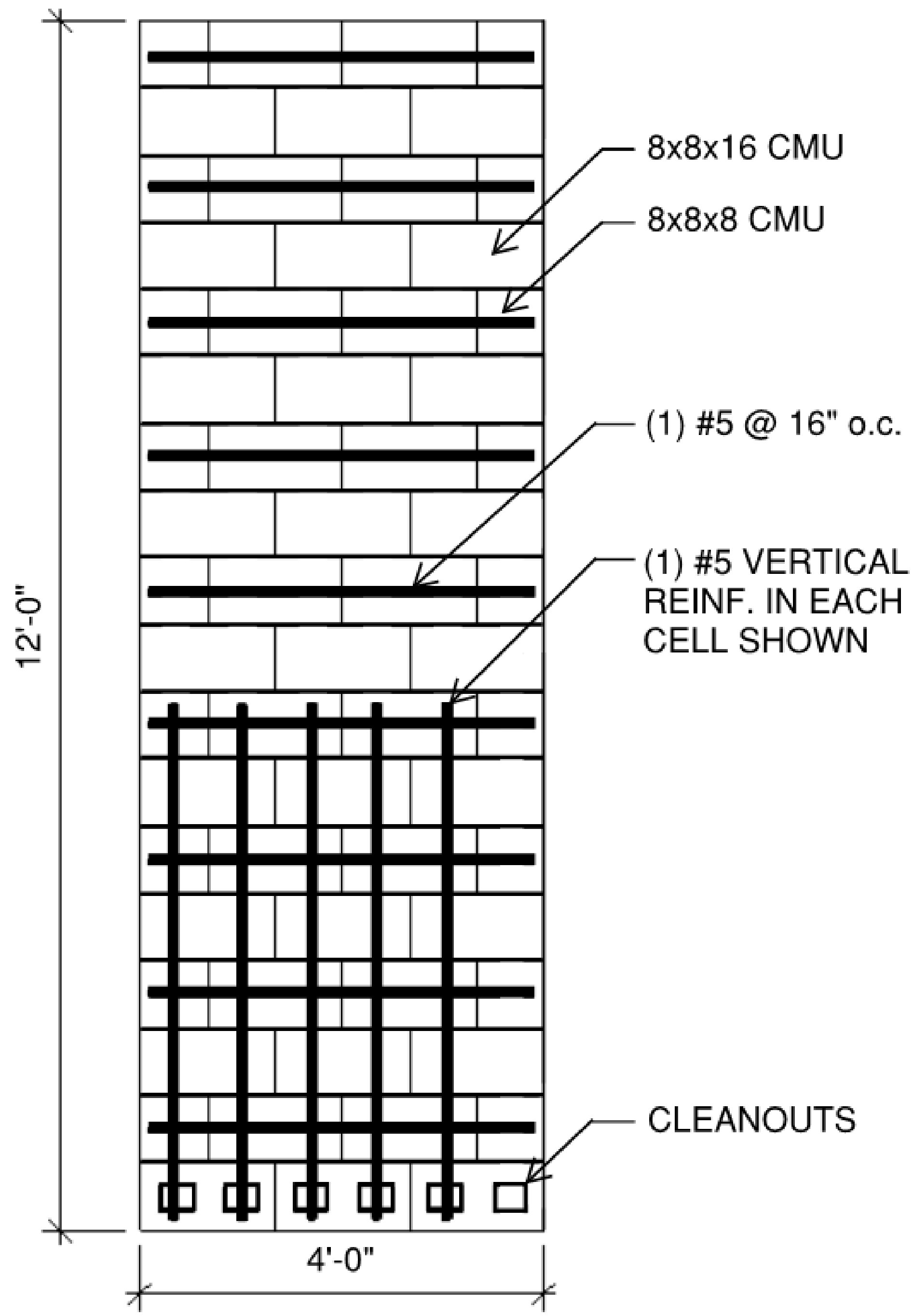


Figure 13: *As-built wall elevation*

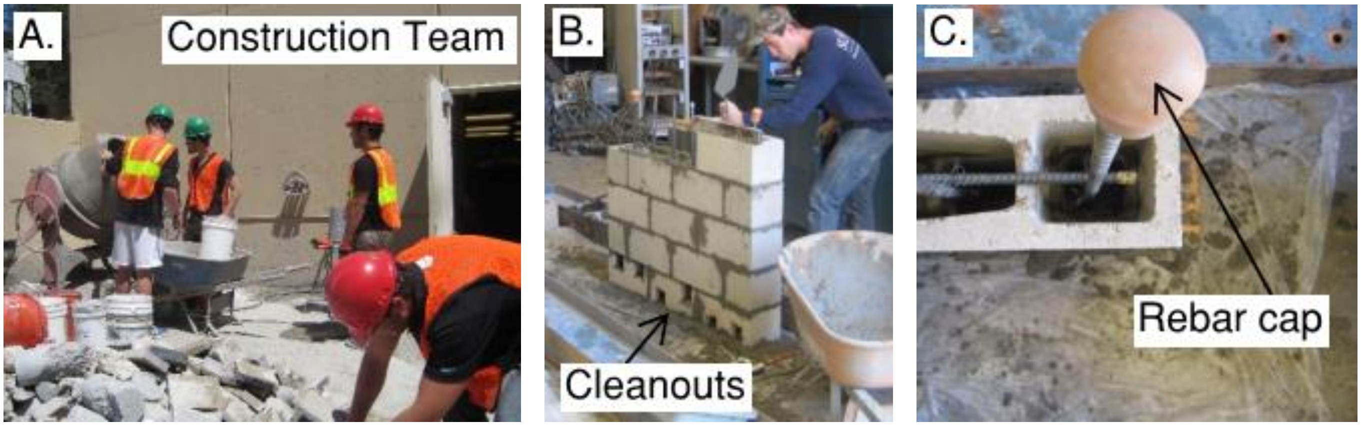


Figure 14: *Wall construction*

Grouting

Based on test results for design grout mixtures listed in **Table 1.1** and **Table 1.2** (see **Appendix A** for complete set of test results), 70SF8 was selected to grout the wall. All materials were proportioned by weight in wheelbarrows and buckets available in the Concrete Lab. Amounts of each material were measured out, accounting for 70% of the total volume. Extra bracing was added at the cleanouts (see ***Figure 15a*)** due to large head pressure demands during grouting. The batched materials were mixed in a mechanical mixer (see ***Figure 7a***) per ASTM C 476. Before the grout was transported to the High Bay Lab, each batch was sampled and tested to determine slump flow; conducting a slump flow test per ASTM C 1611 ensures consistency between batches. The grout was transported in five gallon buckets immediately after mixing. The buckets were raised to the top of the wall with the assistance of a forklift operator. At the top of the wall, the grout was remixed and poured into each grout cell through a funnel created using a traffic cone and a five gallon bucket (see ***Figure 15b*** and ***Figure 15c*** for grout pouring procedure). The process was repeated until the wall was fully grouted, thoroughly washing the mechanical mixer, the funnel, and the buckets after every batch.

Figure 15: *Grouting*

Curing

Once fully grouted, the wall was left undisturbed to cure for a period of at least 56 days after grouting. No mechanical vibrations were applied after grouting.

Lowering Wall

Since the curing period will extend past the 11-week timeframe provided for the project, the remaining tests and procedures will be performed in the future after the wall is fully cured. The wall will be lowered by means of forklift and crane, both available for use in the High Bay Lab. With the wall confined with boards of lumber and straps, the forklift operator will tilt the wall having it lowered with the overhead crane until reaching a horizontal position.

Cutting Wall

Using the forklift and the overhead crane, the wall will be transported outside of the High Bay Lab and placed on a raised, level surface until cutting takes place. The wall will be cut with a diamond blade handsaw in order to obtain test specimens for assessment.

Assessment

Five 2-block high test prisms (8x8x8) were filled with grout on the same day the wall was grouted. Test prisms will be tested to determine compression strengths of final grout mixture after curing. Compression specimens will be cut into 4x4x8 samples and marked to assess consolidation characteristics in cells. Additional compression test specimens will be cut from the wall for assessment (see ***Figure 16*** for cut-locations).

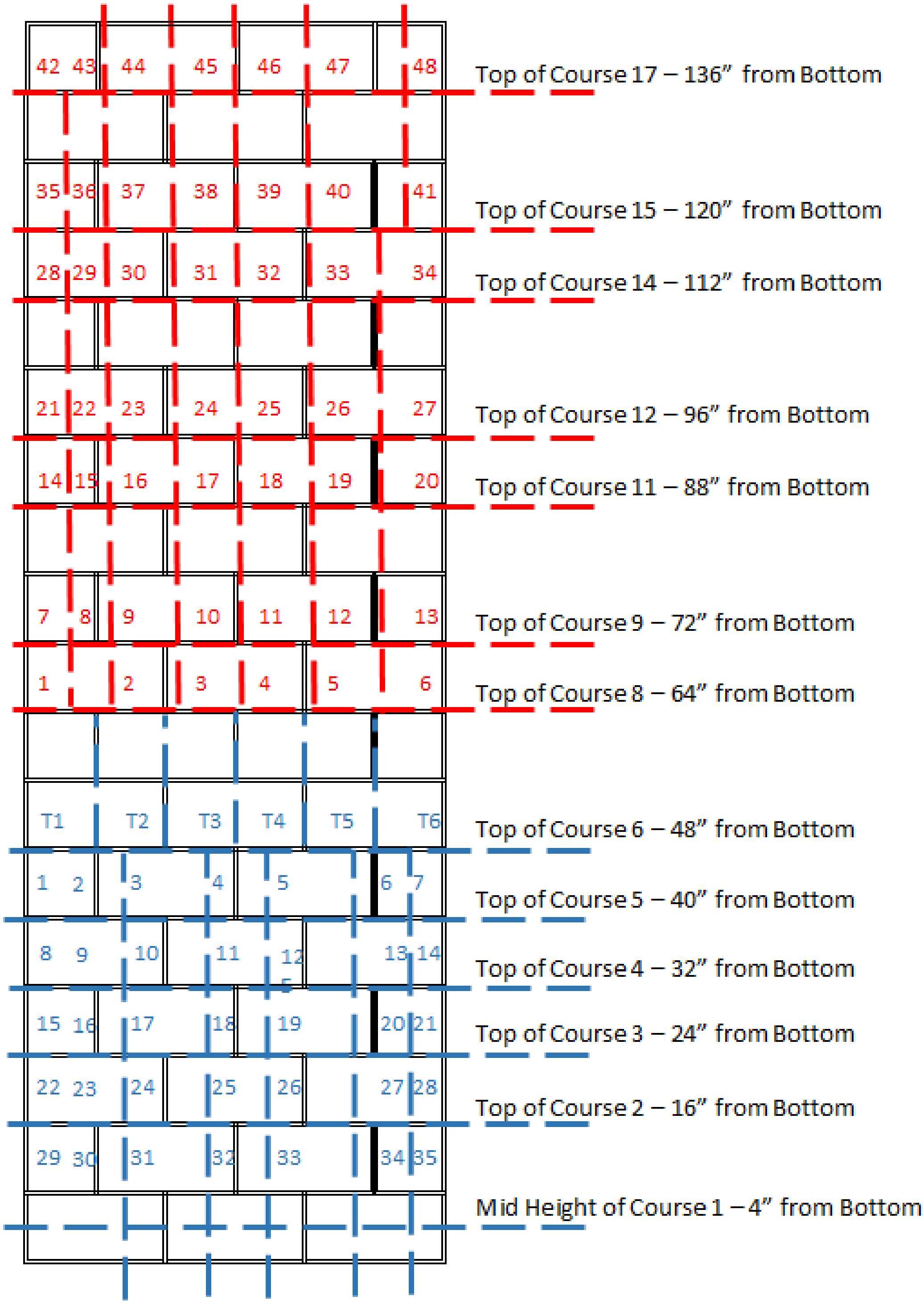


Figure 16: *Cut-locations*

The Design-Build Experience

What is design-build?

"Design-Build is a method of project delivery in which one entity – the design-build team – works under a single contract with the project owner to provide design and construction services. One entity, one contract, one unified flow of work from initial concept through completion – thereby re-integrating the roles of designer and constructor." (http://www.dbia.org/about/Pages/What-is-Design-Build.aspx). DBIA In this project, the design-build entity consisted of an interdisciplinary team of 3 Architectural Engineering students—Jordan, Deryk, and Matt—and 1 construction management student—Tanner.

Design-build is an alternative to the traditional design-bid-build project delivery method. Under the latter approach, design and construction services are split into separate entities, which lead to work getting done independently as opposed to a cohesive team. This project delivery method is divided into several contracts for the design and construction of different aspects of the project. Design-build is beneficial to how we want the project to be accomplished for multiple reasons. It is an effective project delivery method in terms of time, which is beneficial to us because of the tight schedule. Design-build methods are also beneficial to project delivery because they tend to ensure better quality control. For instance, during the construction of the wall, the mixes had to be proportioned to very specific weights as well as mix properly during the mixing process. Each member of the team was able to check what was being done by each person. By doing this, we streamlined the process by having multiple meetings a week setting goals for the project before the start as well as during the execution, and having all members meet for all aspects of design and construction.

Design-Build Institute of America (DBIA)

We were able to find a lot of information on the design-build process through DBIA, the Design Build Institute of America. Here, we were able to find general guidelines and “mini practices” that aided in creating an effective design-build environment. The 3 critical aspects that contribute to successful design build project delivery, according to the DBIA are communication among members, integration of team members via work sharing, and collaboration of the project delivery process (see ***Figure 17***).

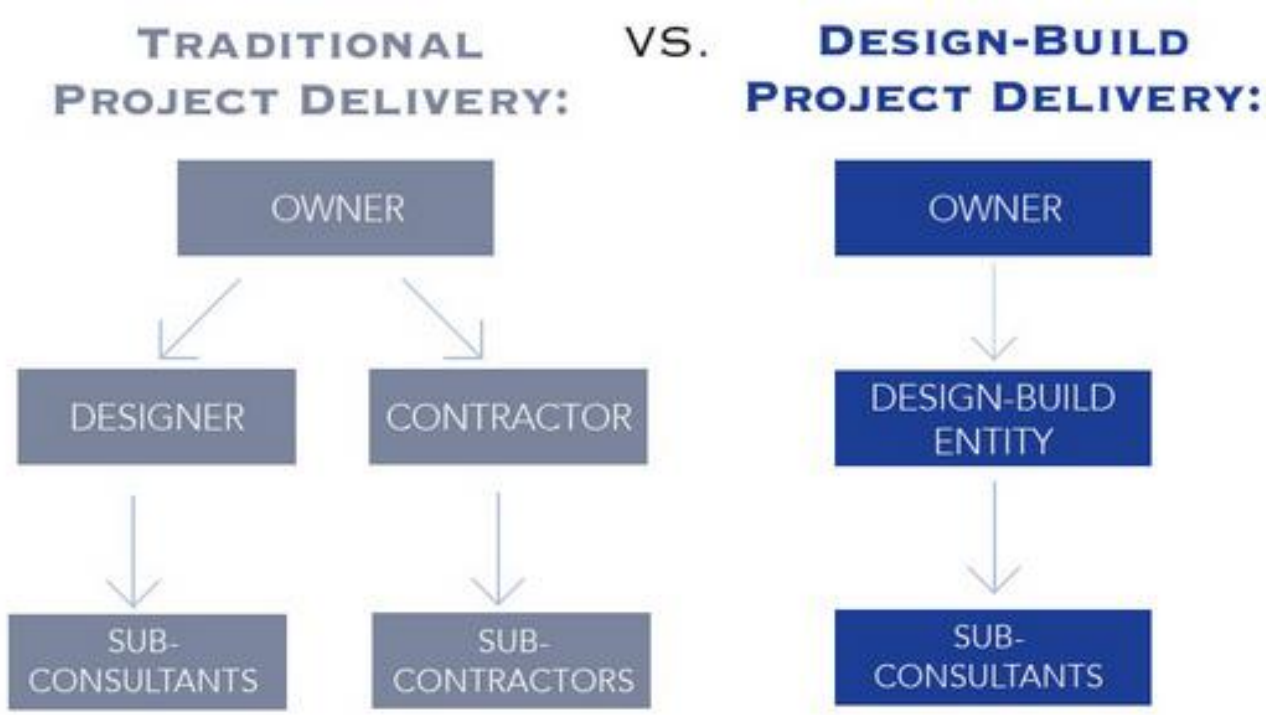


Figure 17: *Design-Build project delivery in comparison to Traditional Project Delivery methods*

Collaboration

Often, in traditional project delivery, disputes between the designer and the contractor may arise, simply because there is a lack of communication. On the other hand, in design-build, both the designer and the contractor are working alongside one another, often sharing workloads and consulting with one another directly. This collaborative environment fosters greater efficiency in project progression, increased quality assurance, fewer change orders, and greater cost efficiency.

However, design-build practices have some drawbacks in comparison to design-bid-build project delivery practices. For instance, because both the designer and the contractor are to work as a single team, oversight must be maintained to ensure quality control. This can be difficult in terms of team work. Also, due to tight schedules and pressure for fast track delivery, another characteristic of design-build project delivery, there can be an overlap of workloads. The project experiences were thought of as more of a benefit than a setback because in terms of our project, the team was able to experience a different perspective and further understand the work that our counterparts in the construction industry provide.

There were a lot of aspects in the project directed by the construction manager. In order to expedite the project, some tasks needed additional expertise. Preliminary mix designs were formulated by the engineering students; this included an estimate for grout and block quantities needed for testing and construction. The construction management student was in charge of creating a material takeoff and estimate for both assembly of the testing apparatus and wall construction after the engineering students had accomplished the design aspect. The team also needed a testing area that could be used for the duration of the project that was secure and protected. The construction manager coordinated with the lab manager in the Cal Poly High Bay

Laboratory where and when the construction could take place. In all of these cases, both disciplines came to an agreement as to what and how each thing should be done (See ***Figure 18***).

Figure 18: *All disciplines on site working together*

Integration

Throughout the process, both the construction manager and engineers had to come together to plan out what preliminary tasks had to be accomplished for the testing, mixing, and construction. This allowed the team to execute the aspects of the project in a timely manner. On the job, the engineer is brought out to visually inspect any deficiencies. In a design-build environment, the engineer and construction team are both working together on site. Quality control is assured due to the constant supervision and direction of the engineers. The construction crew, on the other hand, will have the instruction and guidance necessary to get the job done on time and correctly.

From testing the specimens to grouting the wall, both disciplines were always on site. Before arriving to the job, each member needed to know what had to be done that day. The team found it most effective to plan the labor intensive tasks ahead of time. The engineers were in charge of preparing the mix while the construction manager prepared the specimens. On the days that the mix designs were formulated, each mix had to have it's components weighed out and set aside. During testing, one member needed to proportion mix designs, one needed to prepare each of the CMU test blocks, and two needed to mix and perform slump tests. Compression testing the specimens required cutting each specimen out of each CMU block, measuring and recording the test specimen in accordance with ASTM, coating both ends in hydrostone to create a smooth surface, and then performing a strength test. Grouting the wall required the help of a sub consultant, William Beechinor, so that the process could be accomplished with continuity and no delays. This division of work between both disciplines on site was crucial in keeping up with the tight schedule. By having the entire team on site during all aspects of both design and building processes, we were able to be more productive by assigning shared work loads to provide checks by both the design and construction perspectives as well as minimizing time (see ***Figure 19***).

Communication

Communication is vital to any collaborative effort. When tasks are executed on the job site, both the engineers and construction workers must know exactly what needs to be done according to the schedule. For our team, weekly tasks were assigned. These tasks were all tracked on our schedule and summed up in the meeting minutes. It was absolutely necessary that when instruction was relayed from one member to another, everyone was on the same page. This reduced the chance of miscommunication that may result in a setback that would push the project deadline back.

Figure 19: *Construction manager leading the grout pour with fellow engineer.*

Schedule

The schedule was created by our construction management student. The engineering students provided him with the tasks that needed to be done and he put together a day to day timeline on how to accomplish such tasks. This schedule was created at the beginning of the quarter and changed weekly throughout the process. From materials arriving late to minor setbacks, everything was taken into account. Each delay was documented, which pushed back the final finishing date. Some of the delays had to do with the lack of blast slag distributors and a delay with fly ash delivery. Our deadline was pushed back into summer. In the real world, delays on the job site can cost a lot of money and add to the total cost of the project.

Meeting Minutes

The meeting minutes allowed all members of the team to be held accountable for the tasks they were meant to complete by the next meeting. The meetings were specific and followed the schedule. The team was able to set weekly goals and discuss in detail what needed to be accomplished so that the schedule could be met. The meeting minutes were broken down into topics, which were more concisely detailed in the discussion. The action items gave each member (or members) a due date as well as an assigned task that was the meeting minutes pertaining to our project. After they were checked by all of the attendees, a copy of each one was documented for keeping. The team was always on the same page and insured that each member interpreted the topics from the meeting the same way (see ***Figure 20)***.

April 28, 2015 GROUT
Tanner Blumenfeld
Jordan Delfino
Deryk Izuo
Matthew Josten
Duration: 15 minutes

Regarding: Weekly Meetings

Topic	Discussion	Action Item

Lehigh	Contact Joe, Vice President
	• Acquire total cost for project
	  o Blast Slag and Fly Ash prices
	  o High cement replacement
	• Contact List for Jim
		TB 4/28

Mix Design Proportions	Prepare mix designs for testing
	• (4) based on Report
	  o Change water-to-cement ratio
	• (2) based on Individual Research
	  o Custom mix designs
	  o Support with evidence
		JD 5/1

Testing	Coordinate time to test with lab manager • 7 Day Compression Test • 28 Day Compression Test • Ask Ray about sulfur caps	ALL 5/1
Contact Mason	Coordinate availability for Saturday	CVB 5/1

Figure 20: *Meeting minutes documentation and format.*

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<u>Appendix A:</u> Slump Flow Tests, Passing Ability Tests, and VSI

A.1 Test Investigation of Experimental Grouts from Day 1 of Sampling

Date: Friday, May 1
Time: 2:00 PM - 11:00PM
Temperature[D]: High 76°F, Low 51°F, Avg 64°F
Humidity[D]: High 97%, Low 40%, Avg 74%

Mix Proportions and Test Results for Day 1[E]

Mix Name	Cementitious Materials			Aggregates		Water	Test Results		
	Cement, % Vol.	Fly Ash, % Vol.	Blast Slag, % Vol.	Fine Aggregate, parts/#	Coarse Aggregate, parts/#	Water/Cementitious Materials Ratio	Slump, D_1, D_2, D_{AVG} (in.)	J-Slump, D_1, D_2, D_{AVG} (in.)	VSI, Slump/J-Slump
70SF1	30	17.5	52.5	3 x Cementitious Materials	2 x Cementitious Materials	1.375	12.5	13	0/0
							12.5	12.5	
				# Not Measured	# Not Measured		12.5	12.75	
70SF2	30	20	50	2 x Cementitious Materials	2 x Cementitious Materials	1.2	20.5	Not Self-Consolidating	0
							19.75		
				31	35		20.125		
70SF3	30	23	47	2 x Cementitious Materials	2 x Cementitious Materials	1.25	21.5	Not Self-Consolidating	0
							21.75		
				# Not Measured	# Not Measured		21.625		
70SF4	30	25	45	2.5 x Cementitious Materials	1.5 x Cementitious Materials	1.25	22.5	Not Self-Consolidating	0
							21		
				37.5[A]	19.6[B]		21.75		
70SF5	30	25	45	2.25 x Cementitious Materials	1 x Cementitious Materials	1.25	26	22	0/0
							26	22	
				46.25[C]	17		26	22	
70SF6	30	25	45	2.25 x Cementitious Materials	1 x Cementitious Materials	1.25	34	28	0/0
							29.5	27.25	
				44	15.75		31.75	27.625	

Superscript:

A: Weight is representative of fine aggregate proportions of 2.0 times the sum of cementitious materials. The remaining 0.5 was added to the mixture but not weighed.

B: Weight is representative of coarse aggregate proportions of 1.0 times the sum of cementitious materials. The remaining 0.5 was added to the mixture but not weighed.

C: Weight is representative of fine aggregate proportions of 2.25 times the sum of cementitious materials. The remaining 0.25 was added after some mixing.

D: Temperature and humidity for day 1 of testing was recorded without a measuring tool on the basis of weather reports for the day

E: All samples from day 1 were prepared with unsieved fly ash.

A.2 Test Investigation of Experimental Grouts from Day 2 of Sampling

Date:	Saturday, May 2		
Time:	10:00 AM - 8:00PM		
Temperature:	High 74°F	**Humidity:**	High 97%
	Low 65°F		Low 40%
	Avg 70°F		Avg 74%

Mix Proportions and Test Results for Day 2

Mix Name	Cementitious Materials			Aggregates		Water	Test Results			
	Cement, % Vol., #	Fly Ash, % Vol, #	Blast Slag, % Vol., #	Fine Aggregate, parts/#	Coarse Aggregate, parts/#	Water/Cementitious Materials Ratio, #	Slump, D_1, D_2, D_{AVG} (in.)	J-Slump, D_1, D_2, D_{AVG} (in.)	Slump 2[A], D_1, D_2, D_{AVG} (in.)	VSI, Slump/J-Slump
70SF7[B]	33.6	24.6	41.8	2.25 x Cementitious Materials	1 x Cementitious Materials	1.08	24.5	20	20.5	0/1
							24	19.5	20	
	4.5	3.3	5.6	48.65	17.81	14.39	24.25	19.75	20.25	
70SF8	37.2	22.8	40.0	2.25 x Cementitious Materials	1 x Cementitious Materials	1.21	25.5	20	Not Tested	0/0
							23.5	18.5		
	5.4	3.3	5.8	48.31	17.4	17.55	24.5	19.25		
70SF9	37.7	22.6	39.7	2.25 x Cementitious Materials	1 x Cementitious Materials	1.21	31	24.5	Not Tested	0/1
							28.5	24		
	5.5	3.3	5.8	46	17	17.64	29.75	24.25		
70SF10	37.4	17.0	45.6	2.25 x Cementitious Materials	1.1 x Cementitious Materials	1.22	25	22	Not Tested	0/1
							24	21		
	5.5	2.5	6.7	46	18.8	18.00	24.5	21.5		
75SF1	36.2	16.4	47.4	2.25 x Cementitious Materials	1.1 x Cementitious Materials	1.09	21.5	Not Self-Consolidating	Not Tested	0/0
							21			
	5.5	2.5	7.2	45	19	16.60	21.25			
75SF2	36.2	16.4	47.4	2.25 x Cementitious Materials	1.1 x Cementitious Materials	1.09	27	23	Not Tested	0/0
							26	23.5		
	5.5	2.5	7.2	45	19	16.60	26.5	23.25		
65SF1	43.9	16.9	39.2	2.5 x Cementitious Materials	1.1 x Cementitious Materials	1.11	27.5	23.5		0/0
							27	23		
	6.5	2.5	5.8	50.6	19	16.50	27.25	23.25		

Superscript:

A: 70SF7 was the first test of the day, performed in the sun. A second slump flow test was performed to measure the possible effects of the sunlight. The remaining tests, including those performed on day 1, were not subject to sunlight or were subject of negligible sunlight.

B: Sample 70SF7 was prepared with unsieved fly ash. The remaining samples for day 2 of testing were performed with fly ash sieved through a #16 sieve.

A.3 Slump Test for 100% Cement Mix Design

Date: Saturday, May 9th
Time: 3:00 PM - 4:30PM
Temperature: High 68°F, Low 66°F **Humidity:** High 55%, Low 50%

Mix Proportions and Test Results for Day 4

Mix Name	Cementitious Materials			Aggregates		Water	Test Results			
	Cement, % Vol., #	Fly Ash, % Vol, #	Blast Slag, % Vol., #	Fine Aggregate, parts/#	Coarse Aggregate, parts/#	Water/Cementitious Materials Ratio, #	Slump, D_1, D_2, D_{AVG}, (in.)	J-Slump, D_1, D_2, D_{AVG}, (in.)	Slump 2^A, D_1, D_2, D_{AVG}, (in.)	VSI, Slump/J-Slump
Final(70SF8) w/ 100% Cement	100	0	0	2.25	1	0.88	17.5	N/A	N/A	0
							16.5	N/A	N/A	
	16.41	0	0	50.4	17	14.39	17	N/A	N/A	

Appendix B: Grout Compressive Strengths from Compression Experiment

B.1 Compression Test Specimens from Day 1 of Sampling: 7 Days of Curing

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF1	4.75	5.625	7.5	7.5	7	25000	935.7	Conical Failure	8x8x16	1
70SF2	4.75	5.625	7.625	7.625	7	32000	1197.7	Conical Failure	8x8x16	1
70SF3	4.75	6	5.375	5.25	7	28000	982.5	Shear Failure	8x8x16	1
70SF4	4.4375	5.6875	7.4375	7.375	7	33000	1307.5	Shear Failure	8x8x16	1
70SF5	4.625	5.75	7.5	7.4375	7	33500	1259.7	Conical Failure	8x8x16	1
70SF6	4.75	5.1875	3.125	3.1875	7	27000	1095.8	Conical Failure	8x8x16	1

B.2 Compression Test Specimens from Day 1 of Sampling: 28 Days of Curing

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF1	4.625	5	7.375	7.5	28	35000	1514	Conical	8x8x16	1
70SF2	4.625	5.625	7.375	7.5	28	45000	1730	Conical	8x8x16	1
70SF3	4.875	5.5	7.625	7.5	28	32000	1193	Columnar	8x8x16	1
70SF4	4.625	5.75	7.5	7.5	28	45000	1692	Shear	8x8x16	1
70SF5	4.75	5.625	7.625	7.5	28	51000	1909	Shear	8x8x16	1
70SF6	4.625	5	7.5	7.5	28	38000	1643	Columnar	8x8x16	1

B.3 Compression Test Specimens from Day 2 of Sampling: 7 Days of Curing

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF7	4.5	5.375	7.625	7.625	7	34000	1405.7	Conical Failure	8x8x16	1
70SF8	5.0625	4.625	7.5	7.5	7	33000	1409.4	Conical Failure	8x8x16	1
70SF9	3.875	5.75	7.375	7.5	7	28000	1256.7	Shear Failure	8x8x16	1
70SF10	4.5	4.75	7.375	7.5	7	33000	1543.9	Conical Failure	8x8x16	1
75SF1	5.375	4.75	7.5	7.5	7	51000	1997.6	Conical Failure	8x8x16	1
75SF2	4.625	4.75	7.5	7.5	7	26000	1183.5	Conical Failure	8x8x16	1
65SF1	4.75	5.125	7.625	7.5	7	19000	780.5	Conical Failure	8x8x16	1
100C	4.75	5.25	7.5625	7.5	7	70750	2837.1	Shear Failure	8x8x16	1

B.4 Compression Test Specimens from Day 2 of Sampling: 28 Days of Curing

Mix Name	Dimensions		Plumb at Mid-Width at Each Face , in.		Age of Specimen (Days)	Maximum Load, #	Compressive Strength, psi	Description of Failure	Type of Masonry Unit (From Mold For Specimen)	Number of Units (From Mold For Specimen)
	Width of Face (Mid-height), in.	Length of Face Mid-height), in.								
70SF7	4.6875	5.3125	7.375	7.4375	28	47000	1887	Shear	8x8x16	1
70SF8	4.75	5.25	7.625	7.625	28	35500	1424	Shear	8x8x16	1
70SF9	4.6875	5.5625	7.5625	7.5	28	57000	2186	Shear	8x8x16	1
70SF10	4.6875	5.25	7.375	7.4375	28	54500	2215	Conical	8x8x16	1
75SF1	4.6875	5.375	7.5625	7.375	28	76000	3016	Shear	8x8x16	1
75SF2	4.6875	5.5	7.375	7.375	28	56500	2192	Shear	8x8x16	1
65SF1	4.8125	5.4375	7.5	7.5	28	44000	1681	Shear	8x8x16	1

B.5 Compression Test for 100% Cement Mix Design: 7 Days of Curing

Mix	Cement	Fly Ash	Blast Slag	Aggregates, parts		Water/Cementitious
Name	% Vol.	% Vol.	% Vol.	Fine	Coarse	Materials Ratio
70SF8	100.0	0.0	0.0	2.25	1.00	0.88
100%	(16.4 lbs.)	(0.0 lbs.)	(0.0 lbs.)	(50.4 lbs.)	(17.0 lbs.)	14.39

Appendix C: Curing Room: Temperature and Humidity

C.1 Maximum and Minimum Temperature/Humidity Readings

Day	Date	Temperature		Humidity	
		High	Low	High	Low
Fri.	1-May				
Sat.	2-May				
Sun.	3-May				
Mon.	4-May	68	66	55	50
Tues.	5-May				
Wed.	6-May	68	66	75	50
Thurs.	7-May				
Fri.	8-May	66	64	82	74
Sat.	9-May	64	64	83	63
Sun.	10-May				
Mon.	11-May	66	64	86	75
Tues.	12-May	66	64	85	62
Wed.	13-May	66	64	83	55
Thurs.	14-May	66	64	81	55
Fri.	15-May	66	64	82	62
Sat.	16-May	66	64	82	73
Sun.	17-May				
Mon.	18-May	66	64	85	66
Tues.	19-May	66	64	83	68
Wed.	20-May	66	64	83	68
Thurs.	21-May	66	64	84	66
Fri.	22-May	66	64	88	66
Sat.	23-May				
Sun.	24-May				
Mon.	25-May				
Tues.	26-May	66	64	87	67
Wed.	27-May				
Thurs.	28-May	66	64	87	61
Fri.	29-May	68	66	82	62
Sat.	30-May	68	66	85	62
Sun.	31-May				
Mon.	1-Jun				
Tues.	2-Jun	68	66	86	65
Wed.	3-Jun	68	68	83	73
Thurs.	4-Jun	68	68	80	75
Average		66.5	64.8	82.1	64.5

Notes:

1. First group of testing specimen started curing on Friday May 1st. They were left in trash bags for 48 hours and then transfered to the curing room on Sunday May 3rd (still in their trash bags).
2. Second group of testing specimen started curing on Saturday May 2nd. They were left in trash bags for 24 hours and then transfered to the curing room on Sunday May 3rd (still in their trash bags).